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Ordering the Chaos: a Guided Translation of Needs into Product Requirements

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Abstract

The organization of customers' needs and technical requirements in a QFD (Quality Function Deployment) often generates sparse relationship matrices. This entails several difficulties during early design process and collides with general design concepts as good balancing, order and symmetry. The diagonality of the matrix is, in fact, an index of the effectiveness of effective decomposition of needs and CTQs (Critical To Qualities) at an appropriate level of detail. The paper presents a step-by-step procedure aimed at guiding the designer for a correct translation of needs into product requirements. The peculiarity is that the method intervenes at the very early stage of VOC (Voice Of the Customer) translation into CTQs, unlike classical approaches that occurs in successive steps. The procedure consists of an iterative elaboration and re-organization of the information related to the radical innovation of complex products. A validation case, performed in collaboration with a manufacturing company operating in the automotive field, allowed to test the effectiveness of the procedure

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1. Introduction

Quality Function Deployment (QFD) methodology starts with the collection and organization of users needs (i.e. Voice Of the Customer, VOC) that are then put in relation with technical requirements by means of a Relationship Matrix [1]. Numerous industrial and academic implementations over the last decades have shown that effective QFDs relationship matrix should be (nearly) diagonal [2]. A diagonal matrix has no or very little interaction between rows and columns [1]. This reveals a successful process of needs decomposition and clustering.

The diagonality or triangularity [2] of the matrix is, in fact, an index of effective decomposition of needs and Criticals To Quality (CTQs) at an appropriate level of detail. Although the link between a good decomposition and the diagonality of the Relatioship Matrix is not an absolute axiom, it is a useful indication to assess and therefore better organize the matrix.

However, the goal of this work is not to define a universally adoptable theoretical method, but rather to provide a practical approach based of useful structured guidelines to perform a better QFD. In fact there is not a "right" level of decomposition a priori, since there can be different possible ways to fill the relationship matrix, depending on the complexity of the object or the designers goal. Regardless of how it is performed, the diagonalization not only allows to get a cleaner and more easily-readable matrix, but also to facilitate successive QFDs steps. Basically there are two possible strategies for reducing the sparseness of the relationships matrix: (i) *ex-post* mathematical or heuristic approaches for matrix diagonalization; (ii) *ex-ante* design approaches, i.e. organizing the matrix with the help of structured design methods such as Axiomatic Design (AD), TRIZ, etc.

Based on these considerations, the paper proposes an ex-ante approach that takes inspiration from the AD philosophy for the selection and ordering of product requirements and Design Parameters (DP). The method intervenes at the very early stage of VOC translation into CTQs, unlike classical approaches that occurs in successive steps involving Functional Requirement (FR), Design Parameters, Process Variables (PV), etc.

Given the strong focus on the re-organization of customers and manufactures needs, the proposed approach is particularly suitable for radical design improvement of complex products such as automotive or biomedical devices, which pursue high

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quality standards, and keeps the focus on the management of all design inputs.

Next section highlights recent developments in the QFD's early stages. Then, the main section describes a method for the correct translation of needs into product requirements. Next a validation case in the automotive field is presented.

2. Translating customers needs: the QFD approach

During last years the attention on the analysis of needs and their translations into CTQs or FRs has been notable. An example is the renewed pyramid of needs by Kenrick et al. [3], who revised the Maslow's [4] well-known hierarchy. In addition Cascini et al. [5] tried to complete and refine the Gero's FBS (Function Behavior Structure) approach [6] investigating the elicitation of needs and their translation into requirements.

Kenrick et al. [3] refined Maslow's pyramid and based the new version on the premise that our strongest and most fundamental impulse is to survive long enough to pass our genes to the next generation and take care of them, dethroning the self-actualization motive at the top of Maslow's pyramid and replacing it with mate acquisition, mate retention and parenting.

With a more structured approach, Cascini et al. [5] stressed the modeling of the design activities necessary to a clear identification of the Needs to be addressed and to a careful definition of requirements specification. Conversely, Thomson [7], starting from a set of case studies observed in academia (but common also in the industrial world), described a method for stratifying customers' needs into four classes in order to avoid errors and create a well-balanced list of requirements.

Indeed mistakes made during the needs and requirements identification are among the most detrimental, since design specications inuence almost every aspect of the final product. Main consequences include longer development time, longer delivery lead time, and higher production costs. Moreover, misinterpretations in understanding customers' needs can lead to erroneous company strategies and incorrect positioning of a new product on the market. Therefore Thomson [7] focused on the stakeholder identification and classification, dividing them into four groups: (i) stakeholders related to design result (customers, users and clients); (ii) stakeholders related to product life cycle (who are upstream to, downstream to and involved in the design process); (iii) external influences (government, society, environment); (iv) stakeholders externally influenced.

Thomson [7] also created a spreadsheet in which all FRs (and, in addition: Non-Functional Requirements; Stakeholders needs; Constraints; Selection Criteria; Optimization Criteria) can be linked to their source in order not to neglect or exclude any requirement information. Such who-to-what mapping is very useful if included in a logic scheme where the successive step is the what-to-how mapping performed through the House of Quality (HoQ).

The HoQ, one of the main tools of the QFD methodology, is an approach that is well-known and widely adopted both in the academic [8][9] and in the industrial [10] [11] [12] fields. Since its first application, the House of Quality has been modified and tailored to different case studies, melting it with a wide variety of tools. For instance Analytic Hierarchy Process (AHP) [13] approach was incorporated in order to delineate and rank the relative importance weight of expressed judgments for customer needs and functional characteristics [14]. Such method may prove to be insufficient and imprecise to capture the degree of importance of analyzed needs. In order to refine the rating, Kwong and Bai [15] proposed to merge the fuzzy logic with the pairwise comparison.

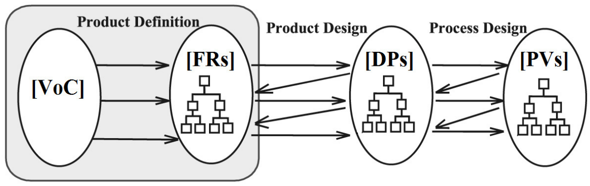

Fig. 1. The Axiomatic Design framework. Adapted from Du et al. [18]

Regarding a methodology for systematically creating technical innovation for new products, Yamashima et al. [16] integrated TRIZ with QFD, proposing a new method named Innovative Product Development Process (IPDP). In the IPDP, a component that requires technical innovation is specified from an analysis of customers' needs by calculating technical mechanism's weight. Then, the technical problems are defined by considering the relationship between the specified mechanism and the corresponding functions or quality characteristics, while technical innovation is executed by applying TRIZ.

In addition, a revisited version of House of Quality has been created to perform a Build-in Reliability (BIR) investigation during a new product development cycle. This tool, called the House of Reliability, enhances the standard reliability analysis introducing and managing the correlations among failure modes, splitting the severity into a detailed series of basic severity aspects and performing a cost/worth assessment to easily evaluate the economical consequences of a failure [17].

The QDF method is based on four subsequent houses of quality in which VoC is translated into FRs, DPs, and PVs. A similar approach was used by Suh [2] to create the AD theory. Such theory consists in a set of rules and axioms that strictly direct designer's work in order to make it faster and more accurate. The mapping process of the above mentioned parameters is articulate according to a zigzag process that enables the designer to deploy each high level parameter into its own low level components only after high level FRs being translated in DPs and PVs. (Fig.1)

Afterwards, these parameters are arranged into matrices in which it is possible to identify their relationships. The AD approach is based on theorems, axioms and corollaries that suggest guidelines for the design process. The fundamental axioms that distinguish such methodology are:

- *Independence Axiom:* maintain the independence of the functional requirements (FRs);
- *Information Axiom:* minimize the information content of the design.

To satisfy the first axiom, the matrix has to be necessary diagonal or triangular. If diagonal, each FR may be fulfilled by one DP independently. This design is called uncoupled design and it is what the designer should tend to. In fact, in case the matrix is not diagonal, parts or aspects of a solution should be decoupled or separated in order to recreate the independence among FRs and DPs, as stated in the first corollary. Suh [2][19] suggested that the methodology can be combined to QFD in order to enhance the design of existing products. In the literature there are several examples of application of AD to QFD, such as in [20] and [21]. In this combination of methods, the correlation among FRs and DPs has to comply with axiom 1, although the model does not use priorities criterion.

For what concerns normalization issues, there are three generally adopted methods for normalizing the relationships among VoC and CTQs. The independent scoring method proposed in [8], consists in rating the importance of each technical characteristic as a weighted sum of need weights and relationship degree. Depending on designer's experience and smartness, the thoroughness given to the detailing of needs and FRs might not be the same. As a consequence, the designer might identify a large number of FRs related to a unique need, instead of recognizing a single and more general FR that groups the more detailed ones. This approach may lead to a distorted relation between the technical characteristic ranking order and the customer requirement one.

To reduce such intrinsic defect, Lyman [22] suggested the normalization of the coefficients in the relationship matrix. By dividing each of the coefficients of a row by the sum of the values on that row, the normalized matrix permits that the sum of the elements belonging to a specific row is equal to 1, so that the technical characteristic's weight truly reflects the customer requirement importance.

An extension of Lymans normalization has been suggested by Wasserman, to solve the problem of interdependent planning characteristics. Wasserman's method [23] is based on the correlation among technical characteristics (*i.e.* the HoQ's *roof*). Interactions are described in terms of values between zero and one (0.1-0.3-0.9). Taking into consideration the roof too, Wasserman takes into account the effect of dependencies among engineering design requirements and normalizes the technical importance of design requirements reducing the weight of correlated characteristics.

Franceschini [9] suggests using the roof and the dependencies among characteristics in order to eliminate redundancies and duplications of characteristics expressed only with different terms. By observing the relationship matrix, it may be noted that in many cases correlated characteristics influence the same customer needs. The idea is to investigate the characteristics that satisfy the same set of requirements. Even if they were only a fraction of the total correlations, they could bring the analysts to reduce the complexity of the QFD and to simplify the analysis of the information contained in the matrices.

Basing on mentioned evidences from the literature and direct experience from the application of QFD approach into different industrial fields, the authors describe in the next section a step by step methodology that aims to guide the designer for a correct translation of needs into product requirements.

3. Strenghtening Needs Translation

The proposed approach is reported in Fig 2. It is composed of three different steps.

Step 1. The starting point is the analysis and clustering of the VoC. Needs can be gathered by means of different approaches/methodologies such as: Brainstorming; Anthropological analysis; Storytelling; User observation; Surveys; Questionnaires; Interviews; Netnography; Focus groups; etc.

From a de-structured set of customers' needs, the purpose is to primarily obtain two macro-clusters: **(i)** needs whose satisfaction is taken for granted: the essential condition for the product to meet the target market; **(ii)** needs that increase customers' satisfaction and product attractiveness: their fulfillment differentiates the product from competitors. This last group can also be divided in turn into two separate clusters, according to the *Performance* and *Deligheters* clusters proposed by Kano et al. [24] in addition to the so-called *Basic* needs. Many different approaches can be used at this stage, such as the mentioned Kano model, but also: Affinity diagrams [25]; Maslows pyramid [4], Cascini's [5] and Thompson's [7] methods; etc. Given a particular product to be incrementally or radically innovated, needs can be *new* (usually belonging to cluster (ii)), but also *old* (usually belonging to cluster (i)), if they still survive from past configurations of the analyzed product. This is the output of Step 1 (Fig. 2).

Step 2. At the second step, all necessary CTQs are defined. During this process, *new* CTQs related to *new* needs are identified, while in some other cases an already existing CTQ belonging to organization's body of procedures and tests can be valid also for a brand new need. This is the reason why the first sub-step (2.1) is the analysis of product's testing procedures already adopted in the organization: if a procedure aimed at verifying the satisfaction of a particular requirement is already adopted, this will be taken into consideration and labeled as *old* CTQ. Later (sub-step 2.2), the identified needs and existing (i.e. *old*) CTQs are put in relation.

In the case that different CTQs refer to a unique need, the procedure pushes the analyst to investigate whether such need should be reframed, detailed or split, or whether additional needs can be included. Conversely, if a need can still not be measured with an already existing CTQ, the analysts (sub-step 2.3) has to define a *new* CTQ aimed at measuring that the particular requirement has been fulfilled. This process is based on the AD's principles aimed at getting the functional requirements independent each other and at optimizing the design information content.

A structured set of *old* and *new* CTQs is the output of this sub-step. The iterative process (sub-step 2.4) has the ideal goal of a diagonal Needs-CTQs matrix (Fig. 3) allowing:

- To identify the possible matrix elements that correlate *new* CTQs with *old* needs. This is positive as it means that a *new* CTQ is able to better measure the fulfillment an *old* need, or that is able to decouple an *old* CTQ;
- To identify *old* CTQs related to *new* needs. This would be a very important finding as it means that an existing test or procedure was monitoring an unknown customer need. As a consequence, the product was providing a not rewarded feature that the user was potentially interested in.

Step 3. This division among *old*/*new* Needs *vs.* *old*/*new* CTQs draws a structured path for next product design steps, making the further building of CTQs-DPs (or CTQs-FRs) matrix an easier process. As shown in Fig. 3, design parameters can be defined following the track established in previous steps and related straight to the previously defined CTQs. This also allows the designer to concentrate the design process on most

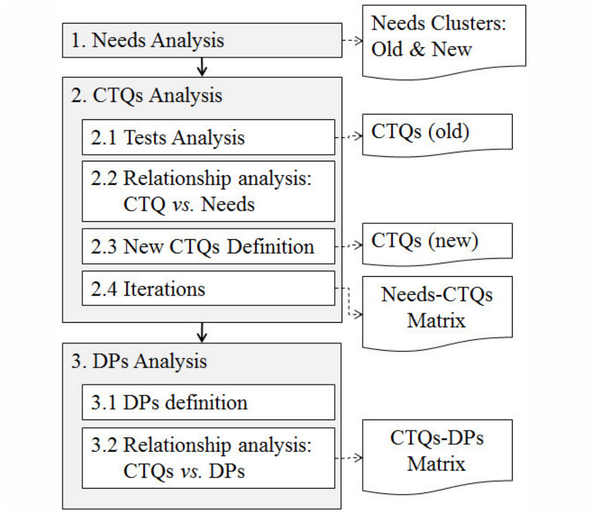

Fig. 2. Process steps for the translation of customers needs into design parameters.

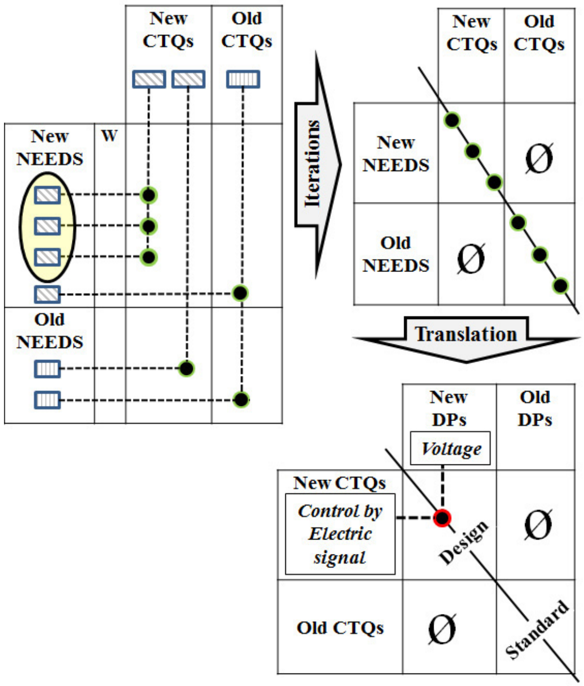

Fig. 3. The process of Needs-CTQs matrix diagonalization. The pursuit of ideal diagonalization allows an easier construction of the CTQ-DP matrix.

critical technical aspects related to the needs that are most relevant for product success. Old CTQs will be linked to already existing and still valid DPs, in a relationship that should be considered as a standard for the organization and for future updates of product's design.

4. Validation case

The proposed approach has been successfully validated in the automotive field for the conceptual design of a radically new window regulator, which is part the new generation of a mechatronic door system. The window regulator was identified as a particularly suitable test case for this methodology due to two factors: level of CTQs definition and product stability over time. In particular, the CTQs tree of this product is typically quite intricate due to the attention to cost optimization, leading to the fulfillment of multiple needs with the same feature, wherever possible. Given the complex nature of the product and the constraints coming from the integration into the door environment, every innovation initiatives should carefully consider all the consequent implications on the whole surrounding system. Therefore an approach that aims at rationalizing the entire information concerning the design variables becomes essential.

Step 1. Firstly a deep investigation of customers' needs has been performed. The 89 collected needs were then divided into three clusters, according to the Kano model. In particular, the team delineated: 14 *Exciters*; 9 *Linears*; and 39 *Basics*. Additional 27 needs, defined "out of borders", were being related to aspects being outside the boundaries of the analyzed system, and taken into account in a second phase of analysis of the needs of the entire mechatronic door system. A successive analysis suggested concentrating on a list of 24 (*old* and *new*) VOC elements composed as in table 1.

Remaining needs, all belonging to *Basics* cluster, were considered for a DFMEA analysis, as most of them could be satisfied by avoiding or monitoring specific causes and failure modes. This is an example of Basic need that can be monitored with a DFMEA: *"Anti-pinch system must be risk-free for the user"*. A final pairwise comparison allowed rating and ranking the 24 needs by means of a linear scale (from 1 for lowest to 5 for the highest level of importance).

Table 1. Set of customers' needs selected from the the 89 collected ones and grouped according to Kanos cluster. Each row reports a real example of collected need, that will be recalled in the following descriptions.

Cluster	Amount	Example
Exciters	14	*Easy to fix during assembly phase*
Linears	9	*Low Electricity consumption*
Basics	1	*To allow functioning if misalignment around Y Axis*

Step 2. The second step concerned the analysis of the current validation tests carried out by the window regulator manufacturer to check the requirements provided by the OEM as well as to verify the binding requirements. The preliminary analysis identified 53 Tests from which to extract the necessary CTQs.

Then, a relationship analysis among the identified tests and the 24 needs has been performed. The 0/1 correlation between a test and a need is verified in the case that the test is able to verify the particular requirement. Partial capacity to verify the requirement is also accepted as the information is still useful for the definition of *new* CTQs. The output of this sub-step was an amount of 18 *old* CTQs deriving from already adopted tests. Additional 11 *new* CTQs have been defined to verify the previously uncovered needs.

The iterative process provided a final set of 29 CTQs and 24 needs related by means of a 24-by-29 relationship matrix reported in Fig. 4. Finally, CTQs' grades of importance have been calculated by means of Lyman scoring method. Calculation were easy as for this intermediate step as the relationship

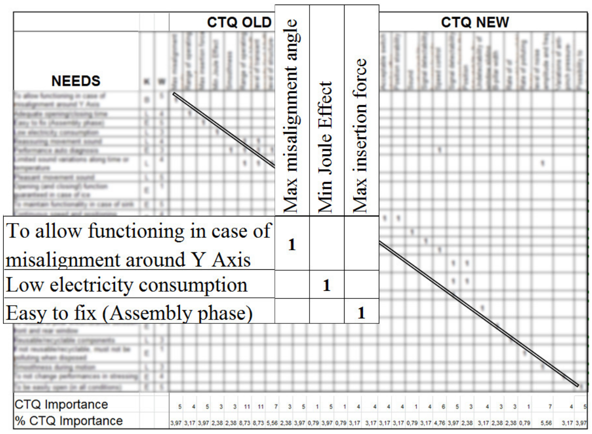

Fig. 4. Needs-CTQs Relationship Matrix. The final configuration tends to be diagonal as pursued. The Figure highlights the three CTQs related to the introduced example needs.

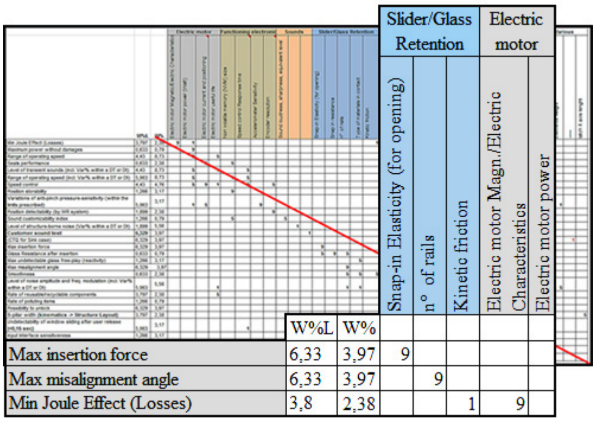

Fig. 5. Extract of the obtained CTQs-DPs Relationship Matrix. The Figure highlights the DPs defined to fulfill the introduced example needs and verified by the relative CTQs. CTQs relative weights are also reported, basing on traditional (W%) and Lymans (W%L) normalization methods.

value could just be 0/1. Resulting weights have been used in the following step.

Step 3. The definition of products' DPs was made by a team of experts from the window's regulator manufacturer.

DPs were grouped in the following functional blocks: Electric Motor; Functioning Electronics; Sounds; Slider/Glass Retention; Gears; User Interface Electronics. At this stage, the correlations among CTQs and DPs have been assessed using a linear scale (1 5 9) and both Independent and Lyman scoring methods were applied to evaluate each DP weight. The result of this step is the CTQs-DPs relationship matrix shown in Fig. 5. The procedure allowed the development of a quasi-diagonal matrix that ensured the designer:

- To effectively manage each DP in order to fulfill a given need whose fulfillment is guaranteed by the related CTQ;
- To concentrate on those DPs that reached the highest weight: the weight value of a particular DP carries the information of importance of the related CTQ and Need.

5. Conclusions

The paper presented a step-by-step procedure aimed at guiding the designer towards a correct translation of needs into product requirements. The work has been conceived starting from the need of an optimized set of relationships among customers' and designer's information during radical design improvement of complex products. The method drives the QFD team through an iterative revision of Needs, CTQs and DPs in order to pursue a well balanced structure. Actually, the target structure could be considered a measure of a proper level of detail of decomposition for all the considered variables.

Such systematic procedure promotes the discussion within the team, makes order during the chaotic early stages of product development and also facilitates the successive design activities.

With this purpose, the authors suggested to start from the collected Voice of the Customer for coming up with a structured set of needs that distinguishes among those needs already monitored by the company and those that are newly discovered. With this information, the designer can better identify the relative CTQs, distinguishing among those already formalized in the form of internal or mandatory testing procedures and those that are newly defined. Proceeding iteratively, the designer obtains an optimized relationship matrix characterized by an high number of one-to-one relationships among customer's needs and CTQs, which allows a better monitoring of requirements fulfillment, as well as an easier definition of products' DPs.

The presented validation case, performed in collaboration with a manufacturing company from the automotive field, provided first evidences of the effectiveness of the procedure. Starting from an high number of collected needs for the development of a new Window Regulator, the procedure allowed the identification of 30 overriding Design Parameters on which the design team will concentrate, while the remaining needs have been considered for being included within the internal standard procedures.

The present work misses the analysis of how the procedure affects the evolution of correlations among CTQs in the HoQ's roof. The hypothesis the authors want to validate is that the method can reduce the number and the entity of such correlations, thus meeting the tendency of paying low attention to this section of the QFD.

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